

Design and Testing of A Global Cloud Resolving Model



Acknowledgments



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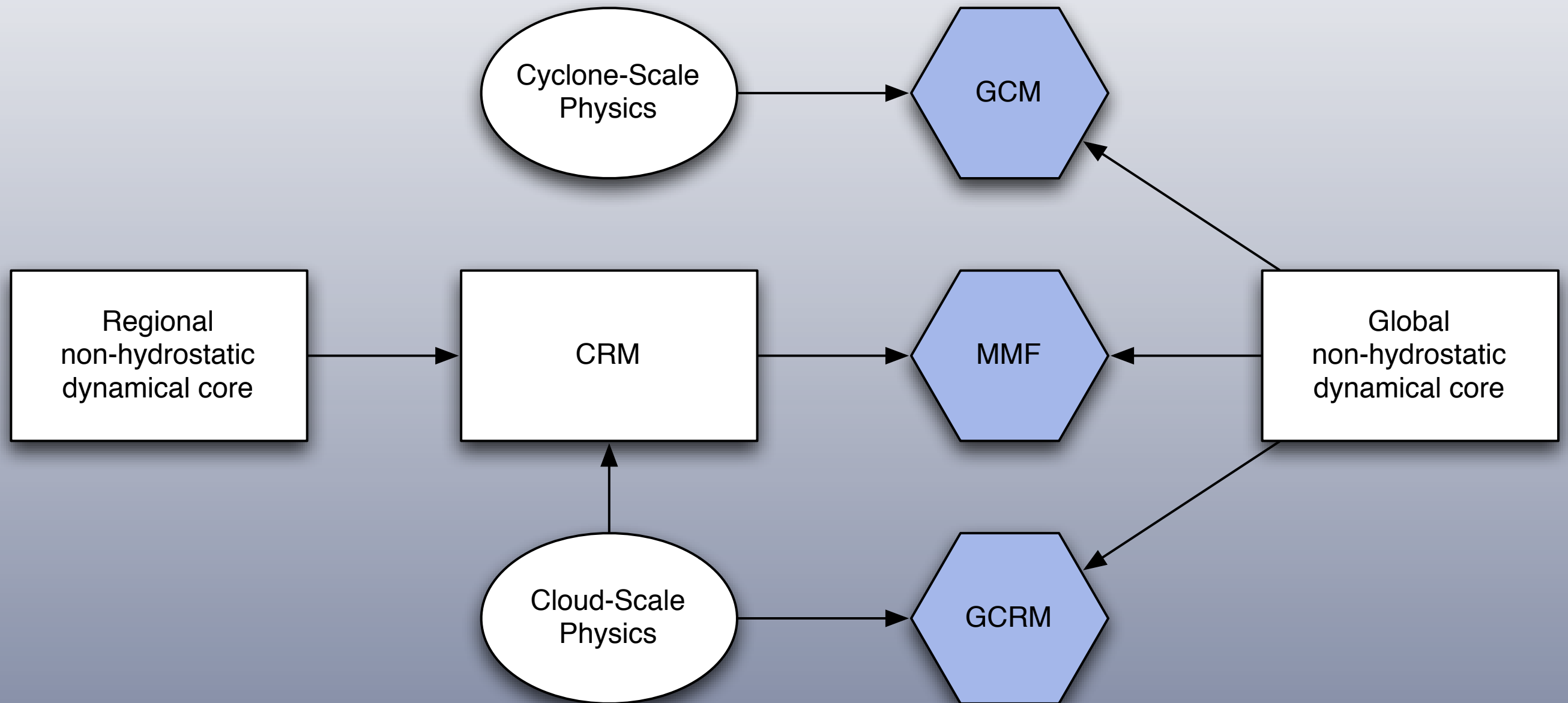


Ross Heikes



Hiroaki Miura

Landscape



GCRM Design Elements

- ◆ **Governing equations**
 - ▲ **Unified system**
 - ▲ **Vector vorticity equation**
- ◆ **Geodesic grid**
- ◆ **Parameterizations**

WHY DO WE WANT TO FILTER SOUND WAVES ?

There is no evidence for the meteorological importance of sound waves.

Non-filtered system :

- Sound waves are generated.
- Models try to *numerically stabilize* those waves.
(e.g., splitting technique, Klemp and Wilhelmson 1978).

Filtered system :

- Sound waves are *filtered at their origin* without depending on numerical stabilization .
- Modeling can concentrate on simulating motions of interest.

Smith and Bannon (2009) showed that filtered models can be more economical than non-filtered models with almost identical results.

FILTERING SOUND WAVES

There are two ways to filter sound waves.

Quasi-hydrostatic system :

$$\cancel{\frac{Dw}{Dt}} + \frac{1}{\rho} \frac{\partial p}{\partial z} = -g$$

Vertical momentum equation
becomes diagnostic.

*To satisfy this for all t , vertical velocity
must be passive to other variables.*

Anelastic system :

$$\cancel{\frac{\partial \rho}{\partial t}} + \nabla \cdot (\rho \mathbf{V}) = 0$$

Continuity equation
becomes diagnostic.

*To satisfy this for all t , pressure gradient force
must be passive to other forces.*



For cloud-resolving models,
filtering must be this type.

The horizontally uniform reference state used in the classical anelastic approximation is unacceptable in a global model, even though it may be OK in a regional model.



THE UNIFIED SYSTEM VS. OTHER SYSTEMS

(a) Compressible non-hydrostatic

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0$$

with no modification of
the momentum equation

(b) Quasi-hydrostatic

$$\frac{\partial \rho_{qs}}{\partial t} + \nabla \cdot (\rho_{qs} \mathbf{V}) = 0$$

with
the hydrostatic equation

(c) Anelastic non-hydrostatic

$$\nabla \cdot (\rho_0 \mathbf{V}) = 0$$

with an approximated
vertical momentum equation

(d) Unified

$$\frac{\partial \rho_{qs}}{\partial t} + \nabla \cdot (\rho_{qs} \mathbf{V}) = 0$$

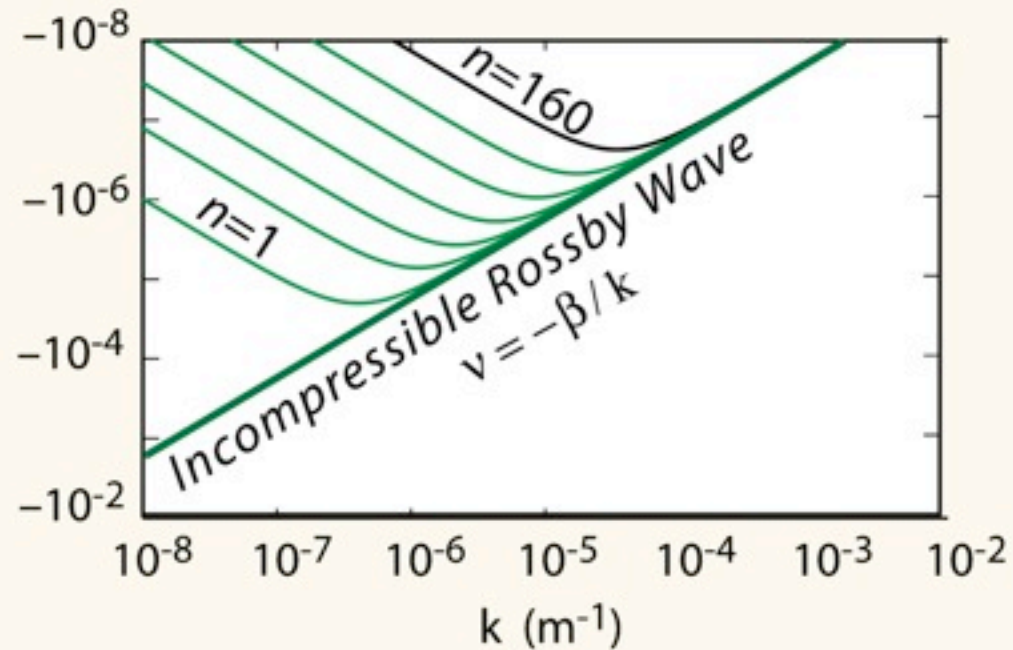
with no modification of
the momentum equation

*The unified system is a generalization of
both the quasi-hydrostatic and anelastic systems.*

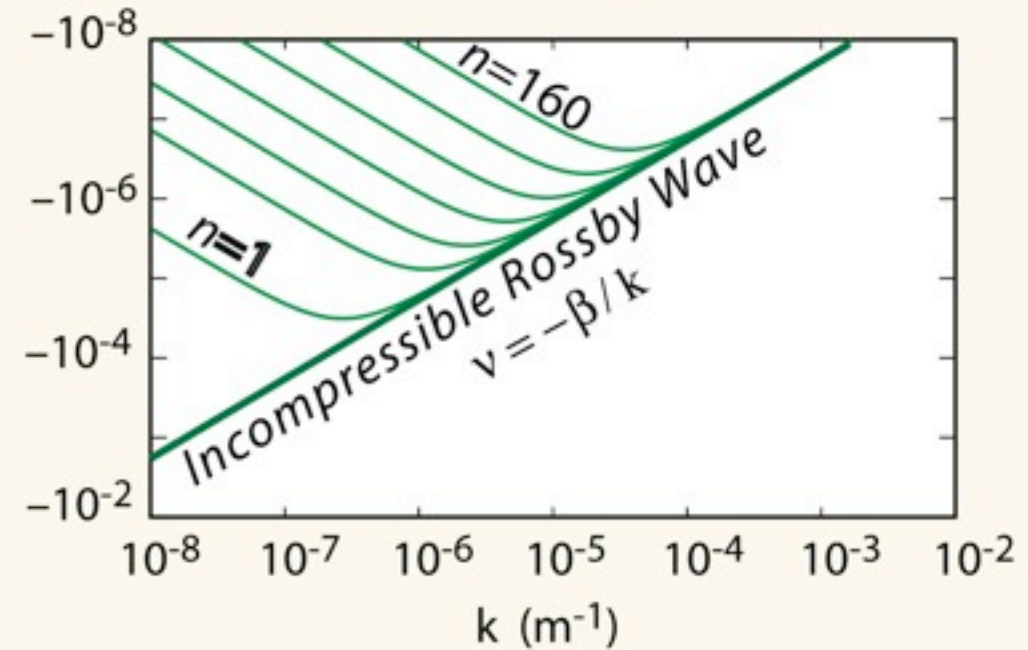
(important in code development and evaluation)

**DISPERSION RELATION FOR PERTURBATIONS
ON A RESTING ISOTHERMAL ATMOSPHERE ON A β -PLANE
(WITH QUASI-GEOSTROPHIC APPROXIMATION)**

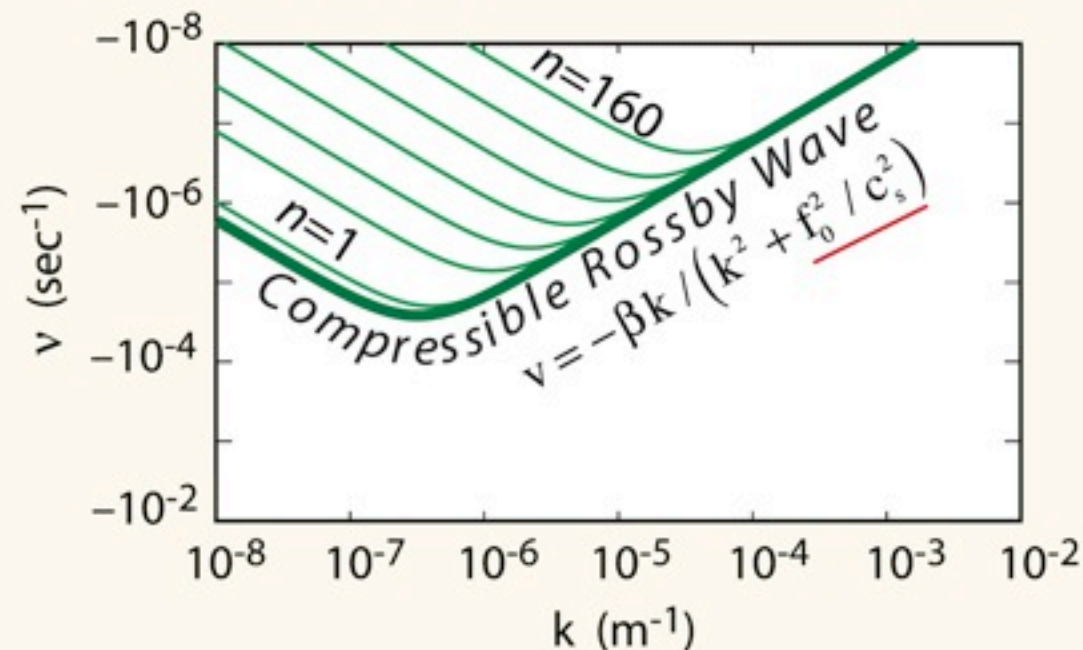
Anelastic



Pseudo-Incompressible



Compressible Non-Hydrostatic, Unified & Quasi-Hydrostatic



Unified System: Summary

- ◆ **Fully compressible for hydrostatic motion, and anelastic for non-hydrostatic motion**
- ◆ **No reference state**
- ◆ **Filters vertically propagating sound waves**
- ◆ **Permits the Lamb wave**
- ◆ **Much more accurate than the anelastic system**
 - ▲ **Global applicability**
 - ▲ **Large static stability, e.g., stratosphere**
 - ▲ **Phase speeds of long Rossby waves**
- ◆ **Conserves mass and total energy**

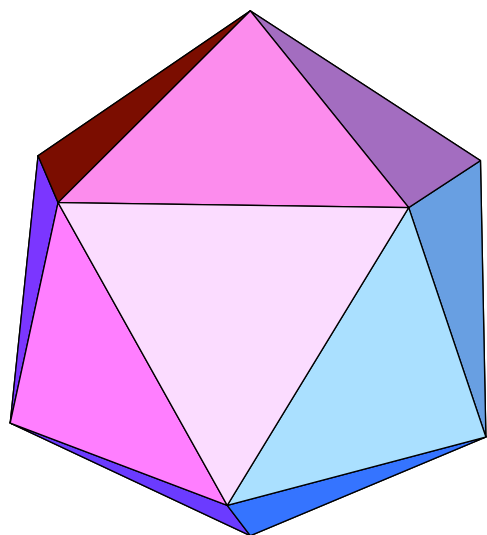
Vorticity across scales



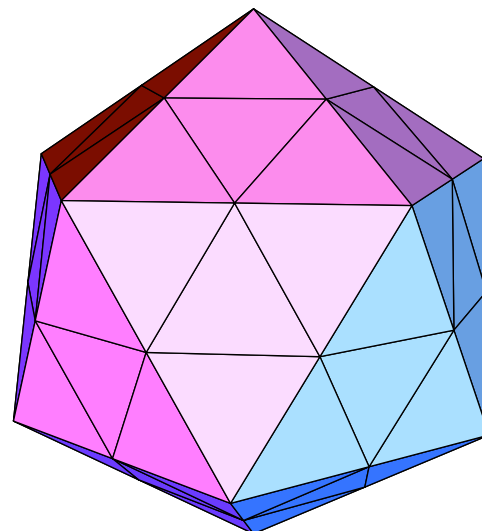
Why use the vector vorticity equation?

- ◆ **The pressure-gradient force is one of the major terms in the momentum equation.**
- ◆ **It plays only a passive role in the anelastic system, often counteracting other forces (e.g., the “virtual mass” effect).**
- ◆ **Therefore, the net effects of forces can be represented more simply if the pressure-gradient force is eliminated.**
- ◆ **This leads to the vector vorticity equation.**
- ◆ **Almost all weather systems are dominated by vorticity.**
- ◆ **A reasonable discretization of the 3D momentum equation does not necessarily correspond to a reasonable discretization of the 3D vorticity equation.**

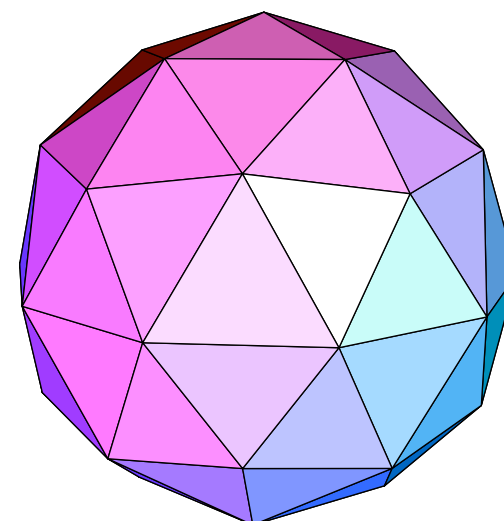
Geodesic Grid



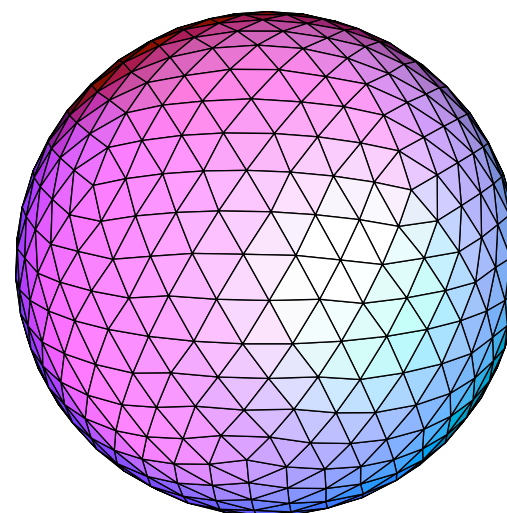
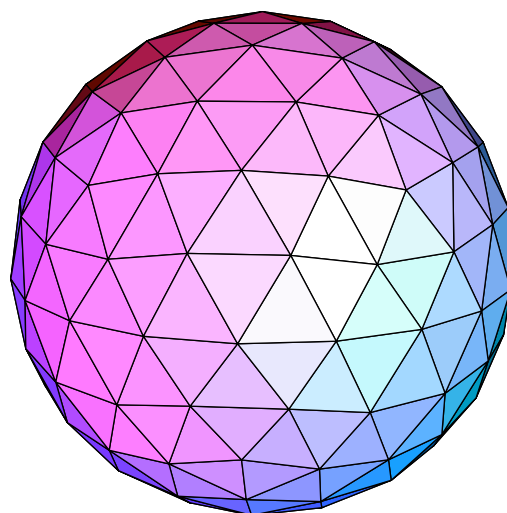
Icosahedron



**Bisect each edge
and connect the dots**



**Pop out onto
the unit sphere**



And so on, until we reach our target resolution...

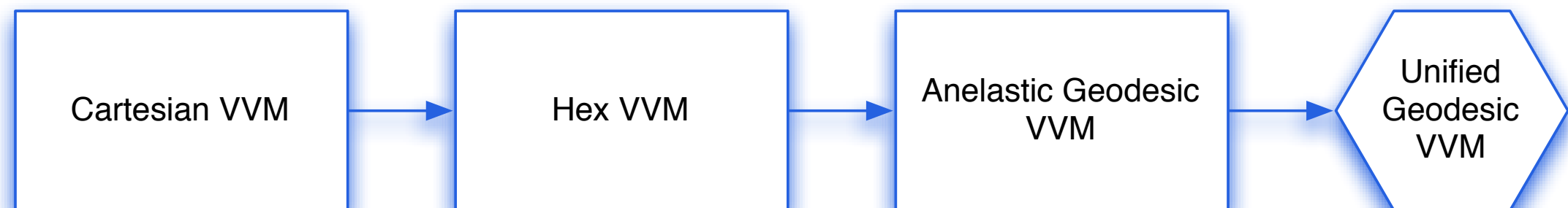
Some grids of interest

Level of recursion	Number of grid columns	Distance between grid columns, km
11	41,943,042	3.909
12	167,772,162	1.955
13	671,088,642	0.977

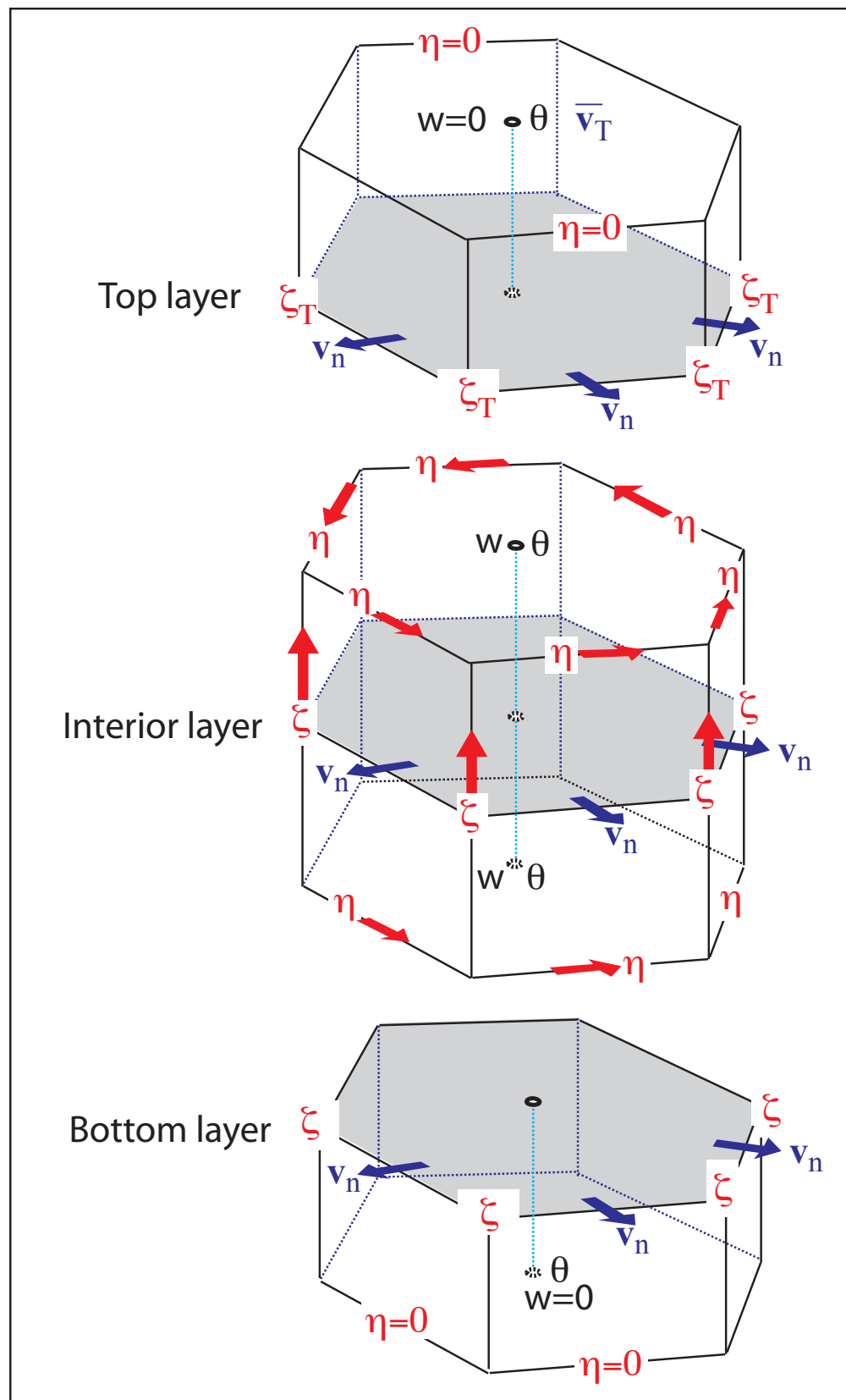
Red Team GCRM	Blue Team GCRM
Unified System	Same
Geodesic grid	Same
Charney-Phillips vertical staggering	Same
Multigrid Solver	Same (but used differently)
Predict vertical component of vorticity, and divergence of horizontal wind	Predict horizontal vorticity vector
Z grid horizontal staggering	C grid horizontal staggering
No computational modes	Computational mode in wind (filtered in tendency terms)

The Blue-Team GCRM

- **Jung and Arakawa (2008) demonstrated the “vector vorticity model” (VM) on a quadrilateral grid with the anelastic approximation, using Lorenz vertical staggering.**
- **Celal Konor has now completed and tested the dynamics of version of the VVM that runs on a plane of perfect hexagons, with Charney-Phillips vertical staggering, still using the anelastic approximation. We call this model the “Hex VVM.”**
- **Physics is being installed in the model now.**
- **The Hex-VVM has been used as a testbed, to find and solve problems that might arise in the Blue-Team GCRM.**



Grid of the Blue-Team GCRM



$\eta = 0$ at the upper boundary.

ζ_T is predicted for the top layer.

The boundary condition $w = 0$ determines δ_T .

\mathbf{v}_n is determined from the streamfunction and velocity potential.

η is predicted at interior interfaces.

ζ is diagnosed from ζ_T and η .

w is obtained from a 3D elliptic equation.

\mathbf{v}_n is determined from η and w .

θ is predicted at every interface.

$\eta = 0$ at the lower boundary (frictionless case).

Lower boundary condition is $w = 0$.

Steps along the way

- ✓ *3D-elliptic solver.* Solve for vertical velocity w using η .
- ✓ *Advection of η .* Predict the horizontal component of vorticity η .
- ✓ *Advection of ζ_T defined at cell corners.* Predict the vertical component of vorticity ζ_T in the top layer.
- ✓ *2D-elliptic solver defined at cell corners.* Diagnose horizontal wind \mathbf{v}_T in the top layer using ζ_T and δ_T .
- ✓ *Advection of θ defined at cell centers.* Predict potential temperature θ .

A simple test of the 3D multigrid solver

- ◆ Prescribed analytic potential temperature perturbation

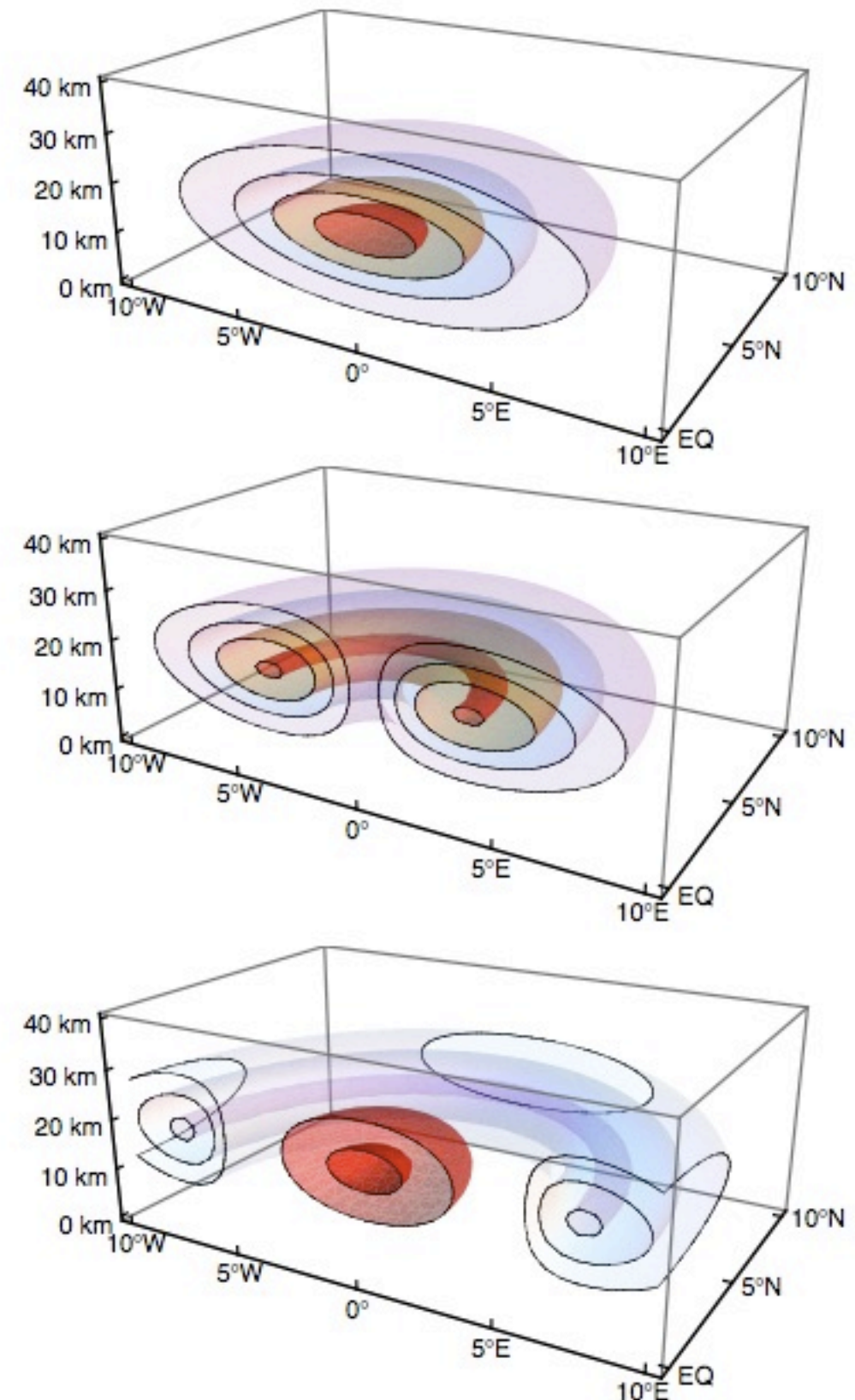
$$B = g \frac{\theta'}{\theta_0 (= 300K)}$$

- ◆ Implied tendency in the horizontal vorticity equation

$$\eta = -\Delta t \mathbf{k} \times \nabla_H B$$

- ◆ Taking the curl forms the right-hand-side of the w equation.

$$\nabla^2 w + \frac{\partial}{\partial z} \left[\frac{1}{\rho} \frac{\partial}{\partial z} (\rho w) \right] = -\mathbf{k} \cdot \nabla_H \times \eta$$



Scaling test of 3D-multigrid on Jaguar

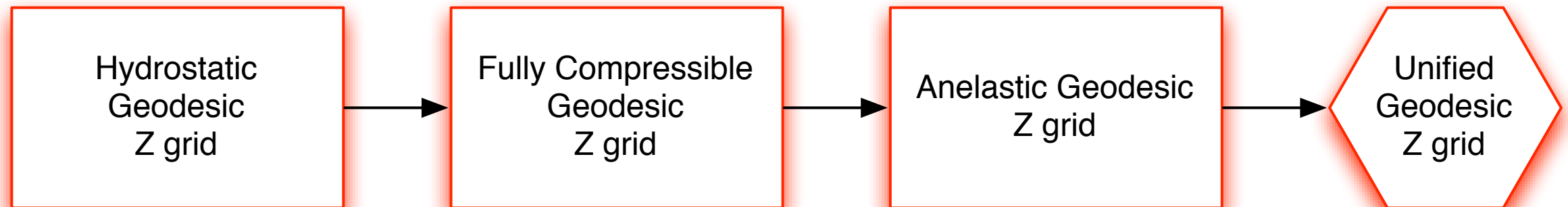
- ◆ The **NCCS Cray XT5** with 181,00 cores
- ◆ 20 V-cycles
- ◆ 80 layers

Time (s)		Number of cores			
		5120	10240	20480	40960
Grid resolution	41,943,042 (11) (3.909km)	8.652	4.535	3.071	2.377
	167,772,162 (12) (1.955km)	35.567	18.071	8.885	5.646
	671,088,642 (13) (0.977km)	insufficient memory	79.85	36.137	18.903

Ongoing work with The Blue Team GCRM

- ◆ **Stretching and tilting terms**
- ◆ **Diagnosis of wind at the model top**
- ◆ **Treatment of the computational mode**

Red-Team GCRM

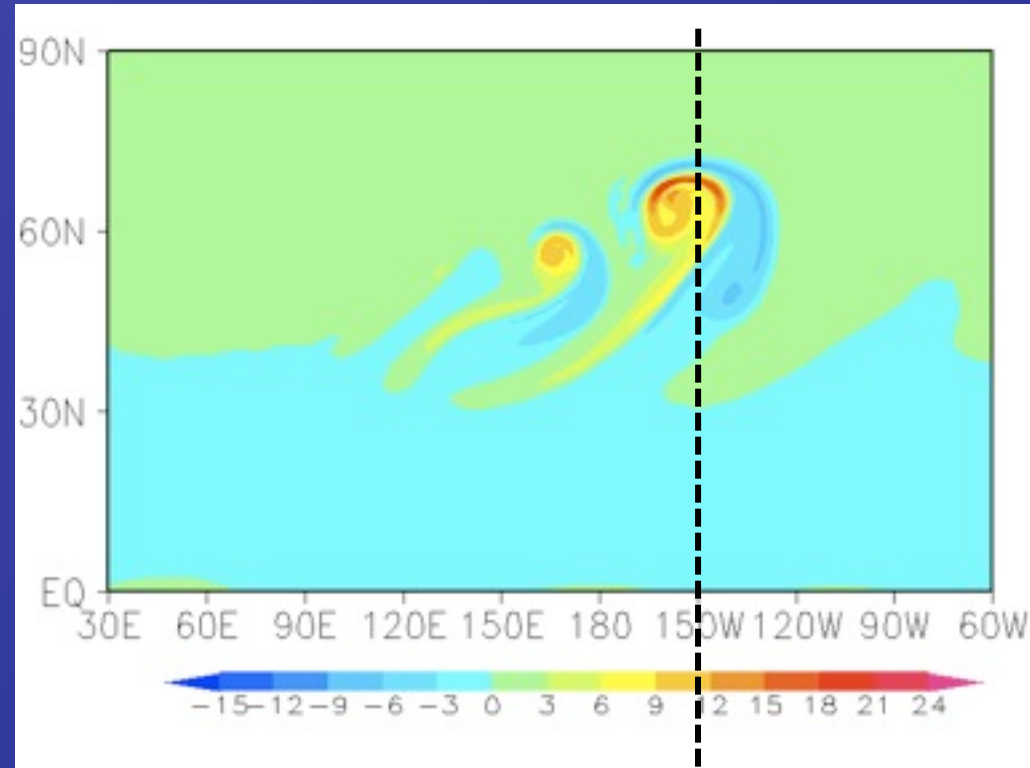


This has all been completed and tested by Hiroaki Miura.

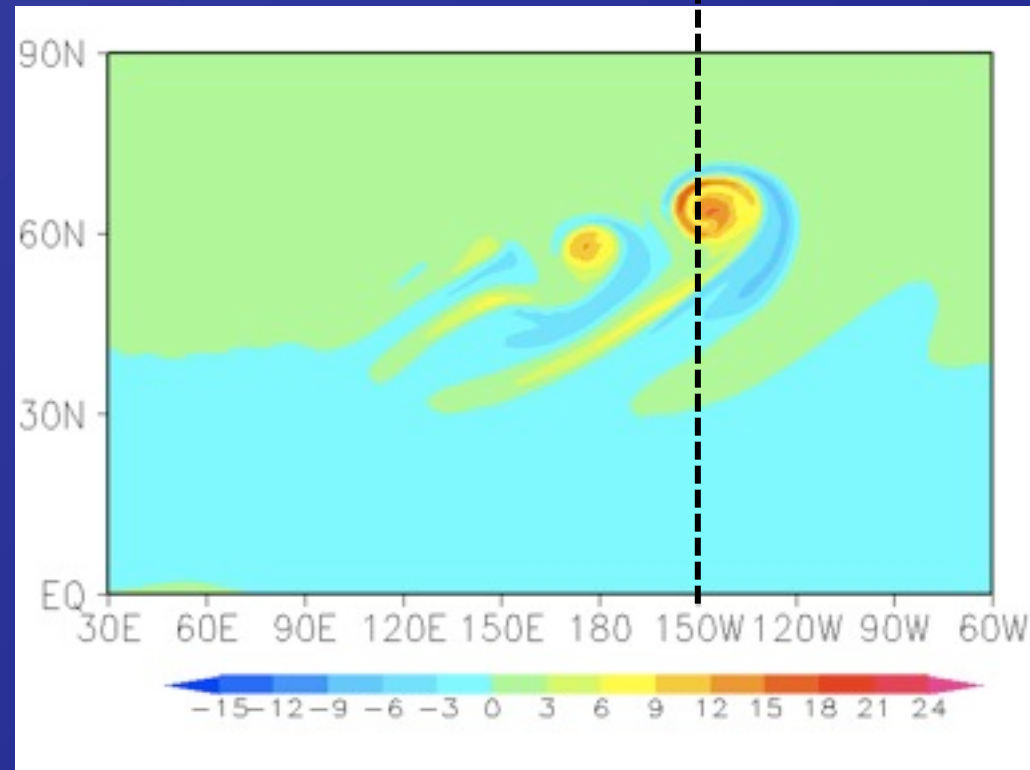
He is now adding the SAM physics (with RRTM) to the Unified Geodesic version.

Unified vs. Anelastic

Unified



Anelastic



Faster propagation of a cyclone and smaller potential temperature advection in anelastic than in unified.

Computing speed

Grid	PEs (Nodes)	GFlop/sec (performance)	Time (sec/day)
5	40 (10)	5.62568 (6.1 %)	35.0308
6	160 (40)	18.1987 (4.9 %)	84.9001
7	640 (160)	63.8086 (4.3 %)	190.9769
8	2560 (640)	171.023 (2.9 %)	566.8823
9	2560 (640)	351.833 (6.0 %)	2287.4747
10	5120 (1280)	696.341 (5.9 %)	*9225.4175
11	10240 (2560)	1406.80 (6.0 %)	*37090.7180

over 1 TFlop/sec

*Estimates from a 12-hours simulation

Performance is a rate against 9.2 GFlop/sec * nodes

Conclusions

- **We currently have a working non-hydrostatic geodesic dynamical core of unique design**
- **Off-the-shelf “local” physics is being added to the model now.**
- **A second non-hydrostatic geodesic dynamical core is nearing completion.**

Landscape

